Final Report
The Dynamics of a Semi-Arid Region in Response to Climate and Water-Use Policy
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Introduction and Project Summary

The objectives of this project were to determine the response of semi-arid ecosystems to the combined forcings of climate variability and anthropogenic stress. Arid and semi-arid systems encompass close to 40% of the worlds land surface. The ecology of these regions are principally limited by water, and as the water resources wax and wane, so should the health and vigor of the ecosystems. Water, however, is a necessary and critical resource for humans living in these same regions. Thus for many arid and semi-arid regions the natural systems and human systems are in direct competition for a limited resource. Increasing competition through development of arid and semi-arid regions, export of water resources, as well as potential persistent changes in weather patterns are likely to lead to fundamental changes in carrying capacity, resilience, and ecology of these regions. A detailed understanding of these systems respond to forcing on a regional and local scale is required in order to better prepare for and manage future changes in the availability of water.

In the Owens Valley CA, decadal changes in rainfall and increased use of groundwater resources by Los Angles (which derives 60-70% of its water from this region) have resulted in a large-scale experiment on the impacts of these changes in semi-arid ecosystems. This project works directly with the Inyo County Water Department (local water authority) and the Los Angles Department of Water and Power (regional demand on water resources) to understand changes, their causes, and impacts. Very detailed records have been kept for a number of selected sites in the valley which provide essential ground truth. These results are then scaled up through remote sensed data to regions scale to assess large scale patterns and link them to the fundamental decisions regarding the water resources of this region. A fundamental goal is to understand how resilient the native ecosystems are to large changes in water resources. Are they are on a spring (remove and return resources, do the systems return to the original state) or a vector (when water returns have the systems fundamentally changed).

The fundamental results of this grant are reported in two peer reviewed publications which are attached to this report. The first was published last year (Elmore et al., 2000) and documents how Landsat TM data can be used quantitatively to document the change in % live cover of green vegetation. This is a key tracking parameter for these systems and the methods developed demonstrate a precision and accuracy of ±4% absolute abundance and ±3.8% year to year change in abundance. The second paper, in the final stages of preparation for submission (Elmore et al., 2001), uses at 16 year data base of Landsat TM derived estimates of % live cover to assess the impacts of climate variability and human response to that variability on the semi-arid ecosystems of the Owens Valley. The time period for the study is 1984-2000 and includes two El Niño periods (early 1980's, mid 1990's) bracketing a significant drought. Here we show that for the valley

Thus to return to the fundamental questions posed by this project (are systems on springs or vectors?) we have determined that water disturbance mediated by human reallocation of resources can results in fundamental changes in the function of semiarid ecosystems. In particular, water disturbance leads to a shift from native shrubs and grasses to non-native annuals (weeds). Based on the presence of weed dominated landscapes that originated from water disturbance in the 1920's, 1960's, and 1970's, there is a high potential that the land cover changes that occurred during the most recent episode of the late 1980's will also have a persistence. It appears that land cover change in these semiarid systems is episodic and coupled to the intersection of climatic variability in the form of drought with increased demands on water resources by social systems. This project may well served therefore as a model for understanding and predicting land use and land cover change in arid regions worldwide.

Fundamental details of the work funded under this effort are to be found in the attached documents.

Outreach

One important outreach aspect of this project is the close relationship we have with the scientists and managers at the Inyo County Water Department. As unfunded co-investigators of this project, they have made valuable contributions to the research. However, they have also benefited greatly from the results and the vegetation change data sets created from the remotely sensed data are now part of the Inyo County GIS. These data are now used on a routine basis to guide resource planning, mitigation efforts, and are a new data set used in the management of water and ecological resources of the Owens Valley. We have kept close communications with the Los Angeles Department of Water and Power as well. They have provided valuable feedback on the utility of the approach and will be considering this technology in future monitoring programs.

Ongoing developments in this project can be found at the following web site:

http://www.planetary.brown.edu/planetary/LCLUC_Owens

Regional Patterns of Great Basin Community Response to Changes in Water Resources

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Introduction

The practices of diversion, exportation, and inter-basin transfer of water within arid environments have increased in frequency and quantity over the past century. Naturally flowing waterways and untapped aquifers are increasingly rare and water extraction has lead to regional groundwater depletion in many areas. The ecological effects of this are particularly obvious in riparian and phreatophytic communities as human populations tend to be biased towards water extraction in these more mesic, and biodiverse ecosystems (Naiman et al. 1993). The possibility for climate change adds a new dimension to this problem. Climate change projections for the next century predict that patterns of annual precipitation may change dramatically (IPCC, 1998). Water inputs from climate are likely to become more and more unevenly distributed throughout the year making necessary the storage (during wet periods) and extraction (during dry periods) of water resources (Field et al. 1999). In regions where extraction already exceeds recharge, the development of water management policy favoring the conservation of natural ecosystems will be of critical concern. The degree to which these water management decisions are based on scientific knowledge will depend on the ability of the scientific community to provide the necessary information at a scale useful for implementation.

At the present, water management policy is formed on only a loose understanding of the consequences of changes in surface and groundwater availability. Studies investigating vegetation change in semi-arid regions have been lacking in either temporal or spatial scale. Several papers have identified species specific groundwater relationships indicating that phreatophytic plants are dependent on groundwater resources for sustained biomass and recruitment (Stromberg, groeneveld, sornsen, others). Still others have identified relationships with climatic gradients (Smith et al. 1990), however few of these studies are longitudinal in nature and most are based on a space for time substitution to predict the possible effects of environmental changes. Furthermore, when longitudinal studies are attempted, they are typically constrained to 2 to 3 years or are of a very small spatial extent due to the time and energy intensive nature of field based analyses. In contrast, water use decisions often pertain to large portions of land, which are difficult to characterize using a finite number of field sites. To understand the long-term consequences of these decisions, we must match our observations of change to the same temporal and spatial scale. In this paper we utilize a 13-year database of vegetative live cover derived from remote sensing data (Elmore et. al 2000) to study changing patterns of vegetation in semi-arid Owens Valley, California. Using remote sensing data to interpolate between field sites is often criticized as being too qualitative or it is applied at a low temporal resolution. However, there are many merits of remote sensing data for regional analyses of vegetation (Tueller, 1987; Woodwell et al., 1984). In our work we use a quantitative measure of percent live cover to characterize vegetation state annually. The unique intersection of large spatial and temporal scale data, with detailed site specific field data, allow us to identify changes in vegetation related to surface water diversion, ground water extraction, and climate variability at a regional scale.

At the large scales discussed here semiarid vegetation can be defined in terms of three broad life forms based on their use of water: xeric, phreatophytic (including riparian), and exotic weeds. This designation is applicable to many semi-arid ecosystems because each community has a universally distinct response to drought. Xeric communities are drought tolerant either by being drought deciduous or by possessing extensive root systems

that are efficient at extracting small amounts of soil moisture. Phreatophytic communities are drought buffered by a ground water table (Sornsen et al). Natural groundwater tables will vary only slightly during droughts and thus buffer phreatophytic communities against water stress. Finally, exotic weeds monopolize on annual rainfall through shallow root systems and survive a period of drought through the utilization of a seed bank (Ref#). Exotic weeds have made a presence on the American semiarid landscape in only the last 100 years (Young et al. 1972), but are increasingly becoming a significant fraction of the live cover.

Research completed to date has all supported the hypothesis that semiarid vegetation is tolerant of drought in the absence of anthropogenic effects. For example, data from tree rings and rat middins in the Great Basin, USA show that over the past 1000 years the region has seen regular 10-20 year droughts, as well as single-year extreme events (Graumlich), yet vegetation communities have remained relatively stable (McAullif, QR paper). Over the last decade, field measurements of semiarid vegetation show similar results (Manning). Vegetation in these regions has been found to be static in areas where anthropogenic modification was minimal.

Detailed field studies lead to the prediction of two deviations to the above model of vegetation stability. 1) Phreatophytic communities are adversely effected by declining water tables (e.g. Manning; Groeneveld et al; Sorenson et al; and Stromberg et al). We expect this response to occur where ground water is extracted for local and regional human use or in regions that had artificially high water tables prior to a drought (often due to recharge from surface irrigation channels). 2) Where precipitation dependent exotic annuals have replaced native vegetation, we expect the plant community to show an amplified response to variable precipitation (Young? ref##). Response to drought typically includes a recovery to natural vegetation conditions, however conversion to an alternate ecosystem type, more competitive given the new environmental variables, may occur. Altered ecosystems may persist or eventually return to a natural state. In the light of continued human manipulation of water resources, the long-term future of these systems is largely unknown.

Our understanding of the dynamics of semiarid vegetation was primarily arrived at through the analysis of field data. However, small-scale changes in topography and geomorphologic features make regional interpolation of field data difficult (Smith et al 1990). Multiple field sites help to constrain our thinking, however field sites will always be limited by uncertainties in identifying specific parameters driving change. For the purposes of management it is critical that we understand the drivers of change at a large scale. A robust model of vegetation response will hold true at larger scales provided the precision and accuracy of the data is comparable to that of field data.

We studied the regional vegetation response to a five-year drought and water management in semiarid Owens Valley, California. Owens Valley is an intensively managed basin east of the Sierra Nevada Range. Los Angeles Department of Water and Power (LADWP) exports surface and ground water to Los Angeles via the LA aqueduct. Beginning in the middle 1980's the actions of LADWP have been regulated by the Inyo County Water Department (ICWD). This relationship has led to an extensive field campaign designed to characterize changes in vegetation and available ground water for the purpose of regulating water export. These data were combined with a simple measure of percent live cover derived from satellite data (Elmore et al, 2000) to characterize the vegetation response over a 13-year period. The goals of this study are 1) to identify the regional consequences of water extraction and climate variability on the semiarid landscape; 2) outline new techniques of quantitative regional analyses; 3) to propose more ecologically conservative water management practices.

Research Approach

Site Description

Owens Valley is a hydrologically closed basin in Eastern California. The valley extends approximately 120 km from north to south and is bordered on the west by the

Sierra Nevada and on the east by the White-Inyo Range. The Sierra Nevada forms a rain barrier, effectively blocking the valley from most easterly flowing winter storms, and keeping median annual precipitation to 13 cm. Each spring and summer, however, abundant runoff from melting Sierra Nevada snowpack flows into the valley and recharges groundwater aquifers. As a result, the ground water table on the valley floor is typically high (Hollett et al., 1991).

The pattern of precipitation between 1984 and 1998 was highly variable (Figure 2). Higher than normal precipitation during the strong El Niño years of 1984 to 1986 was followed by a period of lower than average rainfall to severe drought in 1987 through 1990. Precipitation was extremely variable between 1991 and 1996 with moderate rainfall in 1991, 1993, and 1995, while drought conditions were observed in the alternate years. Finally, in 1996 through 1998, three consecutive years with average or above precipitation rounded off a climatically variable decade.

Owens Valley straddles the boundary between the Great Basin and Mojave Deserts. The valley can be divided into two broad regions: the alluvial fan (bajada) which is a gently sloping region with deep water tables and dominated by xeric species, and the valley floor which is a relatively large (61,500 ha), flat, high-water table basin dominated by phreatophytes. Although the vegetation has been broadly characterized as Desert Saltbush Scrub (Kuchler, 1988) vegetation mapping efforts described by Inyo County and City of Los Angeles (1990) list groundwater dependent scrub, alkali meadow, riparian and marsh plant communities as occurring in the valley. Plant community descriptions follow Holland (1986) and are listed in Table 1.

The dominant phreatophytes of the Owens Valley floor include two perennial grasses and three shrub species. All dominants begin annual growth in spring and reach their peak leaf area by early summer (Sorenson et al., 1991). The grasses are: alkali sacaton (*Sporobolus airoides*) and saltgrass (*Distichlis spicata*). Alkali sacaton is a bunchgrass that may reach 1m in height when it flowers in summer. Saltgrass is a rhizomatous species that is usually less than 30cm tall. The shrubs are: Nevada saltbush (*Atriplex lentiformis ssp. torreyi*), rubber rabbitbrush (*Chrysothamnus nauseosus*) and greasewood (*Sarcobatus vermiculatus*). Mature shrubs range from 0.5 to 2 m tall.

Assemblages of these species can be roughly divided into three vegetation communities: Alkali meadow, Scrub/Meadow, and Groundwater dependent scrub (Figure 3). The grasses dominate the Alkali meadow community, and shrubs, if present, are scattered and contribute less than 30% relative cover. Shrub/Meadow sites have approximately equal proportions of grasses and shrubs, and at least four of the five dominant species are typically present. Groundwater dependent scrub sites average over 85% shrub, and are typically dominated by Nevada saltbush. Scrub/Meadow communities with less than 15% live cover and containing nearly equal proportions of grasses and shrubs are labeled Desert Sink. These Shrub/Meadow communities typically have greasewood and other less common plants as the dominant shrub species and have large bare areas in plant interspaces that are often covered with salt crust. We group Desert Sink communities with Scrub/Meadow communities because these communities require similar groundwater resources. Historic depth to water beneath Alkali meadow in the Owens Valley was approximately 2 m; depth to water beneath Scrub/Meadow and Scrub were approximately 3 m and 4 m, respectively.

The land use history of the region is important in describing the present distribution of plant communities in Owens Valley. Following settlement in 1861, total cultivated land, irrigated land and grazing activities increased until about 1920. Descriptions of the valley from that time indicate that agricultural production covered much of the valley floor and that nearly all of the water from the Owens River was being diverted for this purpose. However, in 1912 Los Angeles completed construction of the Los Angeles Aqueduct, which carried water from Owens Valley to Los Angeles. Los Angeles bought up many of the water rights in the valley and local agricultural production decreased sharply. For this reason, 1920 is viewed as the time when the maximum amount of land was either cultivated or irrigated. In

Owens Valley today, some regions that were cultivated in 1920 have recovered as seemingly natural saltbush and rabbitbush shrublands. However many regions have not been repopulated with native shrubs and grasses and are still dominated by exotic annuals (weeds) such as *Bassia hyssopifolia* and *Salsola kali* var. *tenuifolia.* These areas are mostly found on the eastern bajada and south of the town of Bishop.

The competition for water between Los Angeles and Owens Valley was largely in balance between the 1930's and 1968. In 1968 Los Angeles completed construction of a second aqueduct increasing production by 100%###. Then, when surface water was insufficient to meet the requirements for filling the aqueduct, ground water was used. This practice significantly lowered ground water tables in many areas of the valley. In particular, large changes in depth to water were documented during the most recent drought of the late 1980s and early 1990s. During this period groundwater resources represented a large fraction of total water exported (Figure 2).

Depth to water database

In Owens Valley, 115 shallow aquifer test wells are used to monitor available water resources to phreatophytic plant species. Although each well is checked multiple times per annum, here we use well readings recorded in April. April is generally the month of highest water levels and is before ground water extraction begins for the summer. We view the April well reading as being the most representative of the ground water resources available to phreatophytic plants throughout the spring and summer.

In Figure 4 we present a selection of test well readings distributed throughout Owens Valley. From this Figure it is clear that there is a wide range in the temporal variability in depth to water among Owens Valley test wells. Despite a pronounced 5-year drought many regions did not experience a significant change in depth to water. By significant we refer to a change in depth to water that takes water resources from within the rooting zone of the local plant populations to below that zone (Sorenson et al. 1991). Clearly, the two lightest lines in Figure 4 do not decline below the rooting zone of local meadow grass populations. However, the darkest lines represent decline from within the rooting zones of grasses and/or shrubs to below that zone, potentially causing a negative water stress on the local plant populations.

Of the 115 shallow aquifer test wells monitoring near surface ground water resources available to phreatophytic plant communities, 15 showed only a slight decrease or no measurable change in depth to water despite the 5-year drought. Another 45 wells exhibited a decrease in the water table of about 1-m and therefore may or may not be associated with local plant community stress. Finally, 40 wells showed negative change between 1 and 3 m, while the remaining 15 wells showed a magnitude of change greater than 3 m. Characterization of the impact of these variations in the water table cannot be represented by simple measures such as the difference between before and during the drought. For example, a 3-meter decline in the water tale for a region that supports a meadow community is expected to have a very different effect than a 3-meter decline beneath a xeric shrub community.

Despite its simplicity, we used the before drought-during drought difference measurement in Figure 5 to describe the distribution of pumping activities in Owens Valley. Between the years of 1987 and 1989, ground water extraction was a large fraction of the total water volume exported from Owens Valley (Figure 2). During this period the most intensely pumped regions were the areas north of Bishop, called Laws, and along the western side of the valley between the towns of Big Pine and Independence. These activities are reflected in Figure 5 by the red colored well locations representing wells that recorded a decline in depth to water greater than 1.5m between 1986 and 1992. The region between Bishop and Big Pine is populated exclusively by green and some white colored wells indicating that this region did not experience a negative change in depth to water greater than 1.5m.

A complete explanation of the large regions of ground water decline can not be arrived at solely through the use of the pumping record. In the vicinity of Independence and east of that town, LADWP practiced extensive spreading of water prior to the drought. In years of greater than average snowpack, abundant runoff from the Sierra Range is managed by spreading it over vast areas of the valley floor in the expectation that this water will seep into and thus be stored in the ground water aquifer. Through the early 1980's this practice had the effect of unnaturally elevating ground water tables in this region. Therefore we suspect that declining depth to water in regions of previous spreading is as much a symptom of the halting of these activities as the commencement of ground water extraction. Nevertheless, the effect is the same: ground water levels declined between 1986 and 1992, which was concurrent with a regional drought.

Precipitation Record

LADWP, ICWD, and NOAA currently operate thirteen precipitation gages in Owens Valley. The annual average of six gages that were operational prior to 1986 are shown in Figure 2. Precipitation in Owens Valley typically follows elevation with the highest annual totals found along the northwestern bajada and the lowest found on the southeastern valley floor (Hollet). The variation between gages is typical of semi arid systems. Valley wide the 50-year median for each site is about 13 cm annually.

All six gages recorded below median precipitation for the five years between 1987 and 1992. Significant droughts such as this one are not atypical for the region. Tree ring records from the Sierra Range (Groumlich et al.) and historical records indicate that a drought of this magnitude occurs on the order of every 30 years. In the last century a drought in the early 1930's and another in the early 1960's are documented to have caused regional loss in live cover as well as reduced irrigation for agriculture (#ref). The drought of 1987-1992 is within the normal range of variation for this climate. There are indications, however, that drought frequency and duration may become greater in the near future (IPCC, Field et al. 1999, ref#).

Vegetation Survey

The Los Angeles Department of Water and Power (LADWP) completed a vegetation survey between 1984 and 1987 of all land owned by LADWP. This survey is summarized in Figure 5. Table 1 includes all of the plant community designators used in the survey to describe the vegetation. Plant communities or land covers were delineated from air photos followed by field measurements of the percent cover of all plant species observed in each parcel. The point line transect method (similar to Levy and Madden, 1933) was utilized for, on average, five# 50m transects per parcel.

The ICWD has reinventoried 138 of the vegetation parcels beginning in 1993# to measure significant change since the original survey. Parcels were chosen for reinventory based on their proximity to a well field or rare plant density as well as several control parcels. Manning (ref#) has reported the significant trends and conclusions from the reinventory data. Vegetation parcels located within well fields generally experienced a decline in groundwater tables between 1987 and 1992. This dewatering was coupled with a net loss in live cover, particularly live cover from meadow grasses and phreatophytic shrub species. In control parcels, where the ground water remained at a constant depth, vegetation conditions remained constant.

Example data from field sites exhibiting a variable ground water table and constant depth to water table are presented in Figure 6a and 6b respectively. Figure 6a shows the vegetation data for an alkali meadow community where the depth to the water declined from between -2 and -3 meters to less than -5 meters between 1987 and 1992. This was accompanied by a 75% reduction in % live cover where the reduction was dominated by loss of meadow grass. Increased rainfall and a rise in the water table between 1992 and 1998 were accompanied by an increase in percent live cover. The vegetation cover from the

1998 survey exceeds the cover in 1987, though the dominant vegetation type changed from meadow grass to a mixture of grass, shrubs, and weeds.

A relationship between live cover and ground water resources is also seen in the control parcel. Figure 6b shows the reinventory data for an alkali meadow community located between the towns of Bishop and Big Pine. The ground water table was recorded at -3.5 m in 1986 and increased slightly through the drought. Stable vegetation conditions were observed through this period. Percent live cover decreased only 5% during the drought and the relative abundance of grasses, shrubs and weeds remained constant. These field sites support the thinking that a constant ground water table supports stable vegetation conditions.

The data from these two field sites demonstrate the primary effects of ground water decline on phreatophytic alkali meadow and shrub communities. The complete database of reinventoried vegetation parcels since the original mapping in 1987 further supports these observations. Of the 138 reinventoried parcels, 79 are alkali meadow communities and in 45 exhibited a negative response to declining water tables. Point measurements are invaluable in identifying the floristic component to response, however they can not be used alone to identify either the extent or the location of maximum intensity in vegetation response.

Remotely sensed data

Cloud-free Landsat Thematic Mapper data were acquired during September of each year between 1986 and 1998. Processing of these images followed Elmore et al. (2000). The data set was coregistered to within one pixel, calibrated to a common spectral response using temporally invariant surface features, georeferenced, and analyzed for vegetative live cover using Spectral Mixture Analysis (SMA)(Adams and Adams, Mustard and Pieters). SMA assumes the spectral properties of a given pixel can be modeled as a linear combination of the spectral properties of several endmember materials found in the scene. The proportion of each endmember required to model the spectral properties of a given pixel is a measure of the pixel area covered by that endmember. In Owens Valley, four endmembers representing light soil, dark soil, vegetation and shade were found to best model the total variance between pixels. The resulting estimates of vegetation live cover image were found to be accurate to within +/- 4.0% live cover (%LC). Furthermore, change in live cover was found to be accurate to within +/-3.8%LC (Elmore et al., 2000). The complete 13-year data set characterizes the response of vegetation live cover and is the equivalent of 12 million 30 x 30m plots, in which the total percent live cover was measured every year for 13 years.

We used this database of vegetation to characterize the dynamic properties of land cover. The goal of this analysis was to classify the surface into landcover parcels that exhibited common histories. Simple classification based on the time-history of percent live cover fails to capture the key dynamics expressed in the data since the results are heavily biased by the absolute magnitude of %LC. We therefore develop additional parameters based on the %LC database to facilitate better discrimination of the units.

We first calculated the change since 1986 for each year between 1987 and 1998. In essence the annual vegetation estimate is normalized to the %LC in 1986. This measurement minimized the effect of variation in total live cover and increased the importance of net change. Secondly we calculated the yearly change in live cover for each pair of years between 1986 and 1998. This parameter emphasizes the rate of change in percent live cover which may be characteristic of plant community sensitivity to change (ref#). These calculations enlarged the data set from 13 variables (one for each year) to 24 variables. Two more Landsat derived variables were added to the data set: the mean percent live cover and the standard deviation in percent live cover (as a measure of variability) over the 13 years of the study. Finally, each data point in the percent live cover database was assigned a plant community value from Table 1. This value simply represented the starting

conditions and had no more weight in the analysis than any of the other 26 variables. Table 3 summarizes the data that were compiled into the complete data set.

Before an Isodata unsupervised classification scheme was performed on the entire data stack, the variable mean was subtracted from each data point and then divided by the standard deviation of that variable. This process brought each variable to a common mean and variance and ensured that the Isodata algorithm would weight each variable the same throughout the analysis. Isodata unsupervised classification calculates class means evenly distributed throughout the data space. The algorithm then iteratively clusters the pixels using the minimum Euclidean distance technique. Each iteration recalculates means and reclassifies pixel data with respect to the new means. This process continues until the number of pixels in each class changes by less than the selected pixel change threshold or the maximum number of iterations is reached, which was set at 10 (e.g. Tou and Gonzalez, 1974). We constrained the model to retrieve between 20 and 30 classes and the algorithm formed 23 classes after 10 iterations.

The resulting classification (Figure 5) effectively groups regions of the valley demonstrating a similar response to environmental variables over the 13-year period. The 23 change classes were reduced to 13 by removing 9 classes found to include tilled fields, urban centers, or data errors. The 13 classes are presented in Figure 5 as the average percent live cover calculated for each class over the 13 year period of the study.

Sixteen areas were studied at a scale of 1:12000. Each of these qualitative studies involved comparing air photography with the change classification by creating overlays of the classification. In the field, ##class boundaries were walked and information was recorded as to the perceived live cover, community type, weed fraction, soil color, etc. Strong gradients between regions of contrasting change were traversed and the nature of these communities was recorded. A class description was created for each change class that was used to organize the change classes according to the various drivers and environmental factors.

Results

Phreatophytic Plants and Groundwater

We expect groundwater dependent plant species to show a negative response to the removal of ground water resources. The field data was often ambiguous in testing this idea because test wells in Owens Valley were placed based on proximity to regions of ground water extraction and not necessarily local to vegetation measurement field sites such as the reinventory parcels. This difficulty in comparing the results of the two field based observations was avoided by comparing remote measures of percent live cover with corresponding test well readings. A continuous record of each data type is available from 1986 to 1998 making possible a comparison of vegetation conditions with depth to water.

Man made structures disturb the vegetation such that groundwater resources may no longer limit plant communities in their vicinity. To remove this effect from our analysis we selected the 56 shallow aquifer test wells located in plant communities that were not near a road or other man made structures. Using the LADWP vegetation survey each well was located within one of three vegetation community types: Alkali meadow, Groundwater Dependent Shrub, or Non-native weed. Percent live cover was sampled in a 50-meter radius around each well from the remotely sensed database. These measurements were compared against depth to water readings from each of the wells for 1986 and 1992 (representing maximum change in depth to water.) Figure 7 shows a comparison of the change in vegetative live cover vs. a change in depth to water between these two years. Error bars were derived from the known uncertainty in estimating %LC using SMA (y-axis) and the amount of monthly variation in depth to water for any given site.

Both Alkali meadow and Shrub communities showed a negative change in live cover with a negative change in depth to water. A least squares regression of x and y through each of these relationships proved significant within the 95% confidence limit. Weed

communities (not graphed) did not show a significant correlation with changes in depth to water. Figure 7 lends proof to two points. Firstly, the "treatment" worked in that there was a large range in the change in depth to water beneath phreatophytic plant communities. Secondly, the loss of ground water resources below alkali meadow and shrub communities is correlated with a loss in live cover. We are then justified in identifying a decrease in live cover associated with declining water tables.

In Figure 7 we see that variability in the amount of vegetation change increases with increasing change in depth to water. This is due to the fact that no ecosystem can loose more vegetation than the total live cover prior to the drought. For example, a field site with a pre-drought live cover of 80% can easily loose 50%LC. However, a site with a pre-drought live cover of 30% will never loose more than 30%LC regardless of how much water is removed from the system. This effect may represent a threshold whereby past 2-m groundwater decline in the Alkali Meadow case and past 4-m in the phreatophytic shrub case, these systems loose their total live cover. In Figure 7 we see that change in live cover is highly variable past this threshold, which may indicate this transition.

Xeric Plants, Exotic Plants and Precipitation

Of the two precipitation dependent vegetation lifeforms in the regions we predict that weed species (e.g. abandoned agricultural fields) will show a more amplified response to variable precipitation relative to the native xeric plant communities. Thus, we expect the multitemporal response in %LC of surfaces dominated by non-native weeds to be tightly correlated with the precipitation record and exaggerated relative to native communities. The LADWP vegetation survey, the percent live cover database, and precipitation gages were used to test this idea. Although the precipitation record for Owens Valley shows a valley wide drought between 1987 and 1992 there is some variability among the records of the individual sites. The relationship between precipitation and %LC for weed and native communities is illustrated in Figure 8. This shows data for only two years representing maximum change. The relationship is within the 99% confidence interval for each ecosystem type. In Figure 8a we see that within the xeric ecosystems the largest loss in live cover occurred at those sites that also had the largest decrease in annual precipitation. While the variation between sites was small, the relationship is robust, and demonstrates the inter-annual dependence of xeric ecosystems on precipitation. This result is what we expect given other studies of xeric vegetation(ref#) including a study at a scale similar to that used here. In that study, Smith et al. (1990) successfully showed that the percent live cover of Great Basin vegetation varied with precipitation across regional environmental gradients.

For identical change sin precipitation, we see a remarkably different response for the parcels dominated by weed species (Figure 8b). There is a strong dependence on %LC with precipitation that results in highly variable vegetative live cover on a year-to-year basis. We call this relationship an amplified response to precipitation and it demonstrates that the live cover of weedy species is dependent on available precipitation. In times of drought these communities, primarily found in abandoned agricultural fields, die out leaving the land barren. However, at the onset of a rainy season, the ground will be covered with young Bassia and Sassola recruits. These observations justify this relationship as a fundamental response of semiarid vegetation and we expect it to occur wherever weedy species are present.

Identifying Modes of Response

The 13 change classes in Figure 5 represent units of land cover that exhibit common change in %LC over the time period investigated here. Based on the understanding of the relationships between land cover dynamics and water resources (precipitation or depth-to-water), we can then interpret these responses within the context of anthropogenic or natural systems. The most simply defined land cover grouping is the no change class (labeled NoChg in Figure 5). The vegetation cover on these land surfaces showed little to no variation over the 13 years. While this class encompassed many surfaces dominated by

xeric shrub communities and thus had vary little live cover (typically < 10%), other regions included phreatophytic shrub and meadow communities with substantially higher average live cover. Large areas with high ground water tables exhibiting this response were found between the towns of Bishop and Big Pine and east of Lone Pine. These regions were largely removed from major groundwater extraction wells and thus the water table remained stable. As a consequence the alkali meadow and phreatophytic shrub communities showed little change. Major changes occurring in these regions were primarily associated with reduced surface irrigation or declines in surface flow of the Owens River and associated canal system.

The remaining 490,000 ha of our study area exhibited changes in cover larger than the error in our estimates of live cover (+- 3.8%LC). The first important driving parameter of change was precipitation. Precipitation was sufficiently variable through the period of study to expect vegetation dependent on this resource to change accordingly. Through Figures 8a and 8b we have described the sensitivity of two community types to precipitation. Weedy species were found to be the most sensitive to changes in precipitation. Between 1990 and 1996 (Part B in Figure 9) precipitation in Owens Valley was sufficiently variable to expect a response in precipitation dependent vegetation. We used this time period to identify the degree of correlation between a vegetation change class and precipitation. Vegetation that increased and decreased annually with precipitation was found in the LADWP vegetation survey to be populated by weedy species. After completing a statistical analysis of all of the change classes only 4 were significantly correlated with the average precipitation record. The distribution of these change classes was found to be highly correlated with the sites of abandoned agriculture.

Xeric shrub communities, sensitive to changes in precipitation (see Figure 8) were sometimes confused as precipitation dependent classes. This implies that the isodata algorithm found it difficult to discriminate between a plant community demonstrating an amplified response to precipitation and one with a normal precipitation response. The region on the western bajada between Big Pine and Independence is an example of a xeric shrub community that was identified with an amplified response to precipitation. We have no data to show that weedy species are largely present in this region of the valley, however we do not change this change class because it is representative of weedy plant communities in other parts of the valley.

Test wells in the regions north of Bishop and between Big Pine and Independence recorded declining water tables between 1986 and 1990. This effect is described most clearly in the first frame of Figure 5 and we have shown the dependence of phreatophytic vegetation on groundwater resources through the description of Figures 7a and 7b. Vegetation change in regions of groundwater extraction exhibited a characteristic response to ground water decline and decrease linearly in vegetation cover between 1986 and 1990 (Part A in Figure 9). The change in vegetation cover through this time period is similar to a linear decrease in live cover for those classes associated with a declining water table. Change classes not exhibiting this linear decrease in cover were not found near regions of groundwater extraction. These observations indicate that we can identify regions affected by declining water tables without knowing the exact nature of the water table fluctuations.

Several change classes exhibit some degree of recovery following the drought. Change Class Precip1, for example, shows a response characteristic of precipitation increasing with the return of normal precipitation starting in about 1993. This recovery, however, is not seen everywhere in the valley. The majority of the groundwater related change classes show some recovery, which may be the result of rising ground water tables or increasing precipitation. A comparison of DTW3 and DTW4 from Figure 9 reveals the sharp contrast between the response of vegetation in a region of ground water recovery (DTW4) and the same for vegetation in a region of groundwater decline and no recovery (DTW3). For example, the field site illustrated in Figure 6a is located within change class DTW4. Vegetation in this parcel is recovering, though we note that a large fraction of the new vegetation is weeds. Thus a proportion of the increase in live cover is due to increases in

weedy live cover correlated with precipitation. The average recovery rate for change class DTW4, however, is faster than that for Precip1. This fact, coupled with a clear return of phreatophytic species as seen in Figure 6a, lead us to conclude that the increase in vegetation cover is a result of both a rise in the ground water table and increased precipitation. We have identified this result in 2 of the 6 DTW change classes. These two classes represent 10% of region affected by declining depth to water or roughly 1.8-ha.

Discussion of Results

In a strictly field based analysis of vegetation response to environmental drivers a summary of the fraction of the data conforming to a specific model or observation is often a function of the sampling strategy (ref#). The validity of an interpretation analysis is commonly justified on the basis that the sampling strategy was entirely random or unbiased. However this assumption is often invalid. For example, a researcher might unconsciously favor field sites that are easy to access and thus arrive at a result that is biased towards those regions. In our study, no assumptions are necessary because 100% of the Owens Valley is sampled. A summary of the response in vegetation valley wide makes our results more robust because it provides for the regional significance of each response. For example, each region of groundwater extraction is identified by a spatially and temporally continuous measurement of vegetation conditions that identify a gradient in response ranging from large to small changes in live cover.

We summarize the results in Table 4 by listing the percent of our study area (totaling ~900 sq. km) for each type of response. In Table 4, we also present the percent of each response found for each plant community type (plant community designations are listed in Table 1). For example, the three NoChg classes were 10% Alkali Meadow, 56% phreatophytic shrub, 1% riparian, 29% xeric, and 4% other. The NoChg response is clearly weighted towards the phreatophytic and xeric shrub communities. However, there are stable meadow and riparian communities that had access to ground water resources throughout the drought. Communities with a response correlated with declining depth to water were weighted towards meadow communities, despite the fact that phreatophytic shrub communities make up a larger fraction of the total land cover. There are two reasons for this occurrence. Firstly, phreatophytic shrub communities are not as sensitive to ground water decline. An example of this effect is shown in Figure 7 but was also reported by Sornsen et al. (1991). Secondly, land managers in Owens Valley preferentially extract ground water from regions where the groundwater is closer to the surface and meadow communities dominate these regions. A comparison of Frame 1 and 2 of Figure 5 verifies that the wells colored red are spatially correlated with the alkali meadow communities. In areas of high hydraulic conductivity, the zone of influence of extraction wells can extend large distances from the point of withdraw. Therefore, in meadow and riparian communities, neighboring well fields add to the effect of larger declines in live cover.

Large declines in the depth to water occurred in the region north of Bishop and the region between Big Pine and Independence. We identify the change in ground water conditions with two water management drivers. The first of these is ground water extraction, which was practiced extensively in each of the regions of ground water decline between 1987 and 1989. Groundwater extraction, however, can not explain the entire ground water decline recorded between 1986 and 1992. The second driver of groundwater decline was the reduction in recharge from irrigation ditches. During wet years, water is stored by running it through irrigation ditches with the intent that it will seep into the groundwater aquifer. This practice, widely used in Owens Valley, has the effect of raising or sustaining groundwater levels during times of sufficient precipitation. During dry years, however, this practice was stopped at the same time as groundwater extraction was begun, thus helping to lower groundwater tables.

The network of shallow aquifer monitoring wells recorded a significant decline in groundwater tables over the drought period in many areas. Change classes associated with this decline in ground water accounted for 19% of the valley (17,100 ha). The largest

portion of this area was within alkali meadow communities where twice as much area was affected by declining water tables as that not affected. It is partly an act of human nature that the DTW regions are also correlated with the location of alkali meadow communities (compare with frame 2, Figure 5) in that ground water is extracted preferentially from where it is closest to the surface and therefore most plentiful. However, meadow communities in Owens Valley declined in %LC at a rate greater than phreatophytic shrub communities. Phreatophytic shrub communities represented a smaller fraction of the DTW change classes yet these communities represent 40% of the study area and 62% of the phreatophytic plant species.

The range in the response of the DTW change classes in Figure 5 is primarily due to variations between alkali meadow communities and shrub communities. Shrub communities were found preferentially in the orange areas and typically averaged 20-30% live cover before the drought. This value is about half that of alkali meadow communities. In many of these communities the maximum loss in live cover is not a function of maximum decline in depth to water, but instead a function of the total cover of the original plant community and the sensitivity of that plant community to a decline in depth to water. This conclusion is consistent with our findings from the analysis of vegetation response surrounding test wells (Figure 7). The sensitivity of ground water dependent shrub communities to ground water decline is less than that for alkali meadow communities.

In Figure 8 we included only abandoned agricultural lands that were know to be almost all weeds. These plant communities almost exclusively mapped as being correlated with an amplified precipitation record. The totals for the precipitation dependent classes can be found in Table 4 and indicate that 20% of the valley demonstrated this response. However, only 19% of this total was due to barren abandoned agricultural lands. We found that many different plant community types exhibited a response similar to the amplified precipitation record. An analysis of reinventory data demonstrates that weedy species are found in many areas identified as phreatophytic plant communities in the LADWP survey. The phreatophytic plant communities mapped as precipitation dependent for the most part are located just south of the town of Bishop and account for 43% of the Precip change class. There is an obvious explanation for this effect. In regions experiencing stable ground water through the drought there is no obvious ground water decline response. Lacking a dominating response driven by ground water change, the variable pattern of weedy live cover driven by precipitation is the more obvious response. Field data from these regions of primarily phreatophytic vegetation mapped with precipitation dependent change classes record on average 10%## weedy cover.

Weeds were found in regions mapped with a DTW change class. The reinventory parcel data presented in Figure 6a is an example of a plant community that exhibited an increase in weedy cover following the return of normal precipitation in 1993. This effect can be identified in 77 of the 131 reinventoried parcels located in DTW regions of the valley. As a result of drought and ground water decline, we recorded a loss in live cover of 50% to 80% (roughly 10,000 ha). This dramatic loss in live cover had the effect of reducing the competition on weedy species from phreatophytic species. Through this same period, selective pressures from grazing also favored weedy species, thus giving them a large competitive advantage. This advantage made them more successful in colonizing alkali meadow and phreatophytic shrub communities following the return of sufficient precipitation.

A description of the distribution of exotic weeds in Owens Valley, and the entire Great Basin and Range, is far from complete. In Owens Valley there is a dichotomy between abandoned agricultural fields that have regrown with native Great Basin shrub species and those fields that remain as weedy barren land. The presence of agricultural fields abandoned 80 years ago but that today show no evidence of repopulation by natural Great Basin shrub communities indicates that these systems do not recover quickly to disturbance. McAullif showed that climax communities take thousands of years to mature in these low resource environments. Our data would support this conclusion, but it raises more

questions as well. We found a significant portion of land area with an increased proportion of weeds following the drought. An extended analysis will show the fate of these systems, however we suspect that at least some of them will be disturbed beyond an elastic recovery. If every successive disturbance leads to a small fraction of the landscape being converted to weedy land, the eventual progression is towards complete replacement of natural communities.

Currently, 20% of Owens Valley has weeds as part of the species present in the community. Through the extension of field data, we report that between 2% and 5% of the valley saw a net increase in weedy cover following the drought. This is not a large percentage, however, it represents a response that is different than that expected given the natural drought tolerance of these semi-arid communities. Furthermore, this conversion represents a change in the function of the ecosystem from one dependent on ground water resources to one dependent on precipitation. Climate variability, as a part of climate change, has been predicted to increase in the near future. The coupling of climate variability with plant communities more sensitive to changes in precipitation will lead to interesting consequences regarding the conservation of these natural ecosystems.

Conclusions

Extraction of water resources for regional human use has been a topic of concern in Owens Valley for nearly 100 years and has been debated with increasing frequency. A review of the litigation and agreements passed between LADWP and ICWD is a testament to the difficulty scientists have in convincing the public of their understanding of plant water relations. The ground water dependence of phreatophytic plant species is at the pinnacle of this discussion in that ground water resources are in high demand for human use. Researchers from other study areas have reported results which all point towards ground water decline as a source for the loss of riparian and phreatophytic plant populations (ref#). These "oasis" environments found in arid lands all over the world are hot spots for biodiversity (Naiman et al. 1993) and, therefore, should be given particular attention as we search for ways to conserve and protect the land.

Despite the extensive data available and the long history of water management in Owens Valley, this region would still benefit from a more intensive monitoring program including the annual analysis of remotely sensed data. Remotely sensed data such as that used in this study allow for two important types of analyses. Firstly, the identification of critical areas of concern. Field data, while often very accurate, do not allow for fast and effective sampling of vegetation conditions, and therefore, make it easy to miss areas of change that were in some way not expected to change. Remote sensing data can be analyzed on an annual basis across the entire management region thus providing a high-resolution look at vegetation conditions. Secondly, remotely sensed data allow us to interpolate between field sites, thus identifying the regional extent of changes observed at the field site scale. This is a very important procedure towards scaling our understanding of plant community change to the scale of the disturbances we impose on the landscape.

In Owens Valley, we used remotely sensed data to quantitatively measure the response in percent live cover of semi-arid vegetation to ground water decline and climatic variability. The most obvious negative response of the landscape was correlated with regions affected by changing depth to water. For the most part, these regions were alkali meadows, however ground water dependent shrub communities also experienced a net loss on live cover correlated with a decline of water tables. This result corroborated with the findings of other researchers who have identified the loss of riparian and phreatophytic communities due to regional dewatering. Control communities, where the depth to water did not change despite a regional drought, were found to have sustained live cover and plant community function.

Precipitation dependent plant communities were analyzed through a comparison of data from precipitation gages and the remotely sensed results. Xeric shrub communities,

which have a distribution dependent on annual precipitation totals (Smith et al.), showed only small changes due to variable precipitation through time. Our conclusion is that these species are tolerant of short 5-year droughts and build precipitation/live cover relationships over long time scales. Communities of non-native plant species, however, were found to be sensitive to climatic variability. This amplified response to precipitation was most pronounced at sites of abandoned agriculture where weedy species composed nearly 100% of the vegetative live cover. In almost 5% (50-sq. km) of the valley floor the remote sensing database was used to identify an increase in the sensitivity of the vegetation to precipitation. Field data show that this change in ecosystem function is correlated with an increased percent live cover due to exotic weeds. Our result is consistent with the hypothesis that exotic annuals gain a competitive advantage in phreatophytic plant communities when ground water tables decline. This change in life form dominance represents a change in the function of the ecosystem from one buffered from drought by a ground water table to one sensitive to small variations in precipitation. If this change is stable through time and is representative of semi-arid regions as a whole, it would indicate a significant change in ecosystem function worldwide.

Table 1: Plant Community Designations

Community (Holland, 1986)	#parcels	#acres
Non-native and Miscellaneous Lands (9.6%)		
Irrigated Agriculture	222	11218
Urban	69	2405
Permanent Lakes and Reservoirs	10	491
Intermittent Ponds	20	1865
Abandoned Agriculture -Barren	80	6333
Xeric Shrub (22.7%)		
Mojave Creosote Bosh Scrub	11	549
Mojave Mixed Wooky Scrub	50	9124
Blackbrush Scrub	32	3963
Great Basin Mixed Scrub	234	27647
Big Sagebrush Scrub	80	10670
Phreatophytic Shrub (40.8%)		
Rabbitbrush Scrub	83	9675
Desert Saltbush Scrub	38	3364
Desert Sink Scrub	201	23849
Desert Greasewood Scrub	91	25890
Shadscale Scrub	112	20810
Nevada Saltbush Scrub	85	8163
Meadow (24.0%)		
Alkali Meadow	479	44807
Alkali Seep	1	20
Rush/Sedge Meadow	67	3728
Rabbitbrush Meadow	29	1848
Nevada Saltbush Meadow	33	3269
Non-native Meadow	11	517
Alkali Playa	3	384
Marsh (0.3%)		
Transmontane Alkali Marsh	14	711
Riparian (2.5%)		
Modoc-Gr.Basin Cot/Wil Riparian	12	1989
Mojave Riparian Forest	13	1104
Modoc-Gr. Basin Riparian Scrub	29	2098
Tamarisk Scrub	15	648
Woodland (0.0%)		
Black Locust Woodland	2	21

Table 2: Vegetation Parcels by Live Form

Parcel	Grass*	Shrub	Weed	Other	Parcel	Grass	Shrub	Weed	Other
BGP013	20.8	6.1	3.0	1.1	LAW065	2.6	3.3	6.0	2.8
BGP031	19.8	6.8	1.0	1.7	LAW076	0.0	3.9	0.5	0.1
BGP047	24.8	3.2	0.1	5.1	LAW078	21.0	7.3	18.3	0.2
BGP086	13.8	22.2	0.8	0.3	LAW082	1.9	5.9	6.6	0.2
BGP088	4.3	16.3	0.7	0.3	LAW085	9.8	3.2	2.2	0.0
BGP154	5.0	18.5	4.0	0.1	LAW104	0.0	5.6	0.5	0.0
BGP157	6.1	21.1	3.7	0.9	LAW107	24.2	5.8	13.2	0.1
BGP162	1.8	12.0	6.3	0.1	LAW109	8.6	0.4	0.2	0.4
BGP204	8.3	19.8	2.6	0.2	LAW110	22.6	6.8	11.1	0.1
BGP205	9.9	12.0	0.9	0.1	LAW112	5.5	12.3	2.6	0.0
BIS019	0.0	3.7	0.8	0.0	LAW120	15.2	8.1	5.2	0.0
BIS068	1.2	10.2	11.1	0.2	LAW122	51.5	0.7	14.1	3.3
BIS085	13.2	8.2	0.6	0.0	LAW137	4.1	11.6	7.0	0.1
BLK002	1.6	12.0	3.4	0.0	LAW154	0.1	7.0	0.2	0.0
BLK006	6.6	7.6	1.2	0.9	LAW167	0.0	3.0	1.1	0.0
BLK009	14.5	7.9	0.6	0.4	LAW187	13.1	5.0	0.7	0.1
BLK016	8.1	10.6	8.2	0.5	LNP018	18.7	9.5	0.8	0.5
BLK021	4.7	16.8	1.1	0.0	LNP019	11.3	16.2	1.8	0.4
BLK024	7.2	17.5	1.1	0.1	LNP045	18.7	20.8	7.3	0.0
BLK029	0.0	13.1	0.8	0.0	LNP050	22.7	14.2	5.1	0.0
BLK033	5.9	6.1	3.3	0.1	MAN006	13.8	7.5	1.3	0.5
BLK039	13.7	7.6	0.9	0.2	MAN007	2.0	15.3	4.8	0.1
BLK040	3.6	1.8	0.4	0.1	MAN014	7.5	11.5	0.5	0.1
BLK044	7.8	13.2	8.2	0.0	MAN017	0.3	6.7	16.7	0.3
BLK069	8.9	7.5	0.4	0.2	MAN034	6.3	3.7	0.0	1.0
BLK074	16.4	21.8	0.6	0.2	MAN037	3.0	18.6	4.7	0.1
BLK075	12.8	6.6	6.3	0.3	MAN042	1.2	10.4	8.0	0.0
BLK077	5.2	4.3	0.0	0.0	MAN060	38.7	4.3	5.7	28.1
BLK094	20.0	10.0	3.9	0.4	PLC007	2.5	24.0	2.6	0.2
BLK099	44.6	6.3	2.5	0.8	PLC024	28.9	9.8	3.1	1.4
BLK115	13.2	5.3	0.8	0.5	PLC028	17.6	5.5	0.9	0.3
BLK142	13.5	13.9	0.6	0.1	PLC055	0.2	4.2	0.0	0.0
FSL051	26.2	8.4	6.2	0.1	PLC056	3.3	5.3	0.1	0.0
FSL065	18.0	6.0	6.4	0.7	PLC059	4.3	7.5	0.0	0.2
FSL116	21.3	2.0	2.4	4.1	PLC064	0.9	3.8	1.8	0.0
FSL118	0.0	2.6	0.2	0.0	PLC065	0.1	6.1	0.2	0.0
FSL122	0.8	2.1	1.1	0.0	PLC069	0.3	6.9	0.0	0.0
FSL123	37.9	2.8	12.5	1.7	PLC072	1.1	20.7	0.6	0.2
FSL133	0.0	3.9	1.1	0.0	PLC092	2.1	11.4	3.0	0.1
FSL179	25.6	14.4	0.9	0.0	PLC097	34.3	6.4	3.2	0.3
FSL187	33.6	0.2	0.2	1.9	PLC106	6.5	12.4	1.5	0.1
FSP004	3.9	11.0	7.5	0.1	PLC110	0.9	7.9	0.1	0.0
FSP006	6.3	10.6	1.3	0.0	PLC111	0.4	5.7	0.2	0.1
IND011	30.8	7.4	8.3	0.2	PLC113	0.9	12.5	1.4	0.3
IND019	33.6	13.7	5.5	6.1	PLC121	35.3	7.0	5.0	2.8
IND021	18.0	24.6	3.6	0.0	PLC125	2.4	6.5	0.4	0.2
IND035	42.4	4.4	4.5	0.1	PLC136	12.8	10.0	1.7	0.7
IND064	15.9	14.7	2.0	0.0	PLC137	27.5	15.4	1.2	1.5
IND066	3.3	3.4	0.0	0.0	PLC187	0.3	11.8	0.1	0.0
IND067	14.8	15.2	1.3	0.1	PLC193	0.2	8.2	1.5	0.0
IND087	17.3	8.8	0.3	0.0	PLC220	9.7	6.1	8.5	0.1
IND096	3.0	18.5	2.0	0.0	PLC223	11.0	12.7	0.9	0.1
IND099	3.1	8.0	0.0	0.0	PLC239	0.1	8.8	0.0	0.0
IND106	0.9	14.4	2.6	0.0	PLC240	0.4	3.2	0.1	0.0
IND111	10.1	21.5	3.2	0.1	PLC241	0.2	3.3	0.2	0.0
IND119	13.7	5.1	0.5	0.1	PLC246	0.2	3.3	0.0	0.0
IND122	5.1	22.0	4.0	0.0	PLC251	0.1	4.5	0.9	0.0
IND132	1.3	18.8	1.6	0.1	PLC263	1.8	2.7	0.7	0.0
IND139	6.4	17.3	2.0	0.1	TIN006	1.9	5.7	0.0	0.0
IND151	25.8	1.0	0.3	0.0	TIN028	1.8	14.5	0.8	0.1
IND156	20.7	0.1	0.1	0.3	TIN050	26.2	8.3	0.3	0.4
IND163	8.4	5.5	1.0	0.3	TIN064	12.9	16.1	1.9	0.6
IND205	13.2	5.9	4.9	0.0	TIN068	6.9	8.0	0.2	0.1
IND231	0.1	10.0	6.3	0.0	UHL052	0.3	10.4	0.1	0.0
LAW030	7.4	12.0	2.8	0.0	UNW029	14.3	6.3	0.8	0.1
LAW040	0.3	11.9	6.2	0.3	UNW039	11.2	17.9	2.0	0.3
LAW052	7.9	4.8	11.5	0.1	UNW072	0.2	12.0	0.0	0.0
LAW062	3.2	7.5	10.0	0.7	UNW073	0.4	13.3	0.8	0.0
LAW063	1.4	6.4	8.7	0.3					

*Values are average % live cover from 1990 to 1999

Table 3: Variables Used in Classification

Variable	Description
1	Community (see Table 1)
2	1987 change since 1986
3	1988 change since 1986
4	1989 change since 1986
5	1990 change since 1986
6	1991 change since 1986
7	1992 change since 1986
8	1993 change since 1986
9	1994 change since 1986
10	1995 change since 1986
11	1996 change since 1986
12	1997 change since 1986
13	1998 change since 1986
14	1987 yearly change
15	1988 yearly change
16	1989 yearly change
17	1990 yearly change
18	1991 yearly change
19	1992 yearly change
20	1993 yearly change
21	1994 yearly change
22	1995 yearly change
23	1996 yearly change
24	1997 yearly change
25	1998 yearly change
26	13 year mean
27	13 year standard deviation

Table 4: Summary of Vegetation Response as Percent of Study Area

No Significant Change		51%
Alkali Meadow	*10%*	
Phreatophytic Shrub	*56%*	
Riparian	*1%*	
Xeric	*29%*	
Other[*]	*4%*	
Response Correlated with Groundwater Decline		19%
Alkali Meadow	*59%*	
Phreatophytic Shrub	*29%*	
Riparian	*3%*	
Xeric	*0%*	
Other	*9%*	
Response Correlated with Precipitation Variability		20%
Phreatophytic Zones	*43%*	
Xeric	*38%*	
Others	*19%*	
Undefined Response		10%

[*] Other is typically irrigated agriculture, urban, or barren land.

Figure 1. Site map of Owens Valley, California showing study area, local towns, and principle highways.

Figure 2. Recent timeline for Owens Valley, CA showing the valley wide average percent live cover, precipitation annual totals, total water export and total water extracted from groundwater resources. A pronounced drought between 1987 and 1992 is exhibited in all four quantities. During the height of the drought groundwater extraction volumes nearly equaled total water export from the valley.

Figure 3. Phreatophytic plant communities in semi-arid systems are distributed on the landscape in regards to groundwater availability. Meadow communities require the most shallow groundwater tables, followed by a mixture of shrub and meadow grasses, and then pure phreatophytic shrub communities. Xeric shrub communities require no groundwater resources.

Figure 4. One hundred and fifteen shallow-aquifer monitoring wells exist in Owens Valley. A selection of those is shown here to demonstrate the wide variability between locations exhibited by these records. Some wells exhibited little change in depth to water between 1986 and 1998. However, many wells recorded changes in depth to water from within the rooting zone of phreatophytic plants to below that zone. This represents a disturbance to the native plant communities and is reflected by changes in the percent live cover of local plant communities.

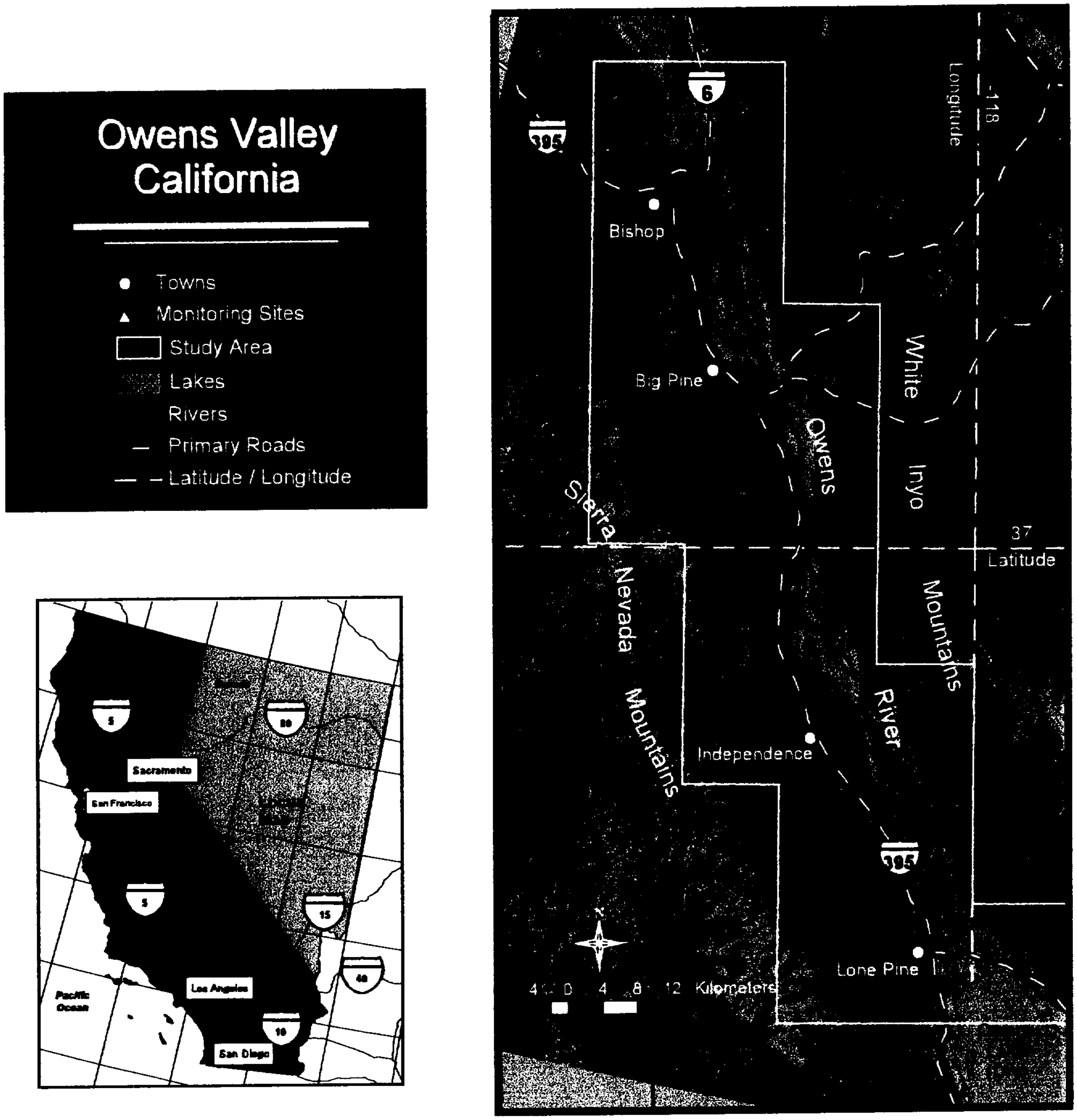
Figure 5. In this Figure we can compare the change in depth to water (Frame 1), plant community distribution in 1986 (Frame 2) and response curve derived from a time series analysis of Landsat TM data (Frame 3) for all of Owens Valley. Regions exhibiting the greatest decline in percent live cover during the drought were located in meadow communities that experienced a lowering of the groundwater table. However, regions between the towns of Bishop and Big Pine supported stable meadow communities despite a regional drought, because of stable ground water conditions.

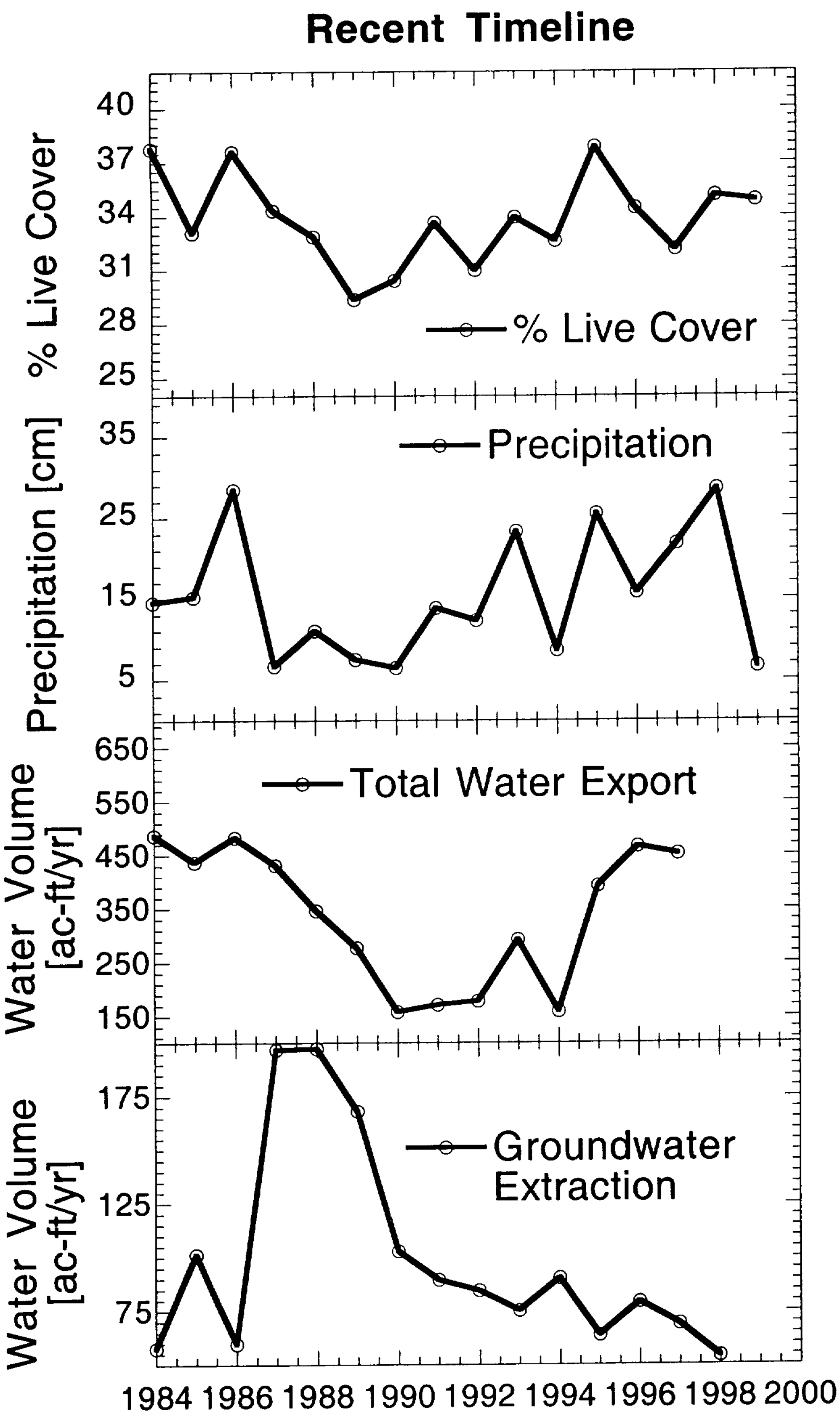
Figure 6. Each graph shows a comparison of floristic vegetation conditions and the depth-to-groundwater as measured in the field. Field sites exhibiting a large decline in depth to water a) often exhibited a recovery following the drought that included an increase in weedy species. Field sites exhibiting stable ground water conditions supported stable vegetation conditions, including a constant relative proportion of grasses, shrubs, and weeds.

Figure 7. A comparison of the change in percent live cover and change in depth-to-water [m] for a) meadow communities and b) shrub communities reveals the ground water dependence of these plant communities. Meadow communities exhibited a response more sensitive to changes in groundwater than did shrub communities.

Figure 8. A comparison of the change in percent live cover and change in annual precipitation [cm] for a) xeric plant communities and b) weed plant communities reveals the precipitation dependence of these plant communities. While dependent on precipitation, xeric communities exhibited much less change in live cover throughout the drought than the more sensitive weed plant communities.

Figure 9. A complete analysis of all modes of response exhibited by Owens Valley plant communities revealed 4 important categories. 1) Communities effected by declining water tables with no recovery 2) communities effected by declining water tables with recovery 3) communities effected by changes in precipitation 4) communities exhibiting very little change to environmental factors.


Owens Valley
California
Towns
Monitoring Sites
Study Area
Lakes
Rivers
Primary Roads
Latitude / Longitude
Sacramento
San Francisco
Los Angeles
San Diego
Pacific Ocean
5
80
15
40
10
6
395
Longitude
-118
Bishop
Big Pine
White
Owens
Inyo
Sierra
Nevada
Mountains
37
Latitude
Mountains
River
Independence
Lone Pine
N
4 0 4 8 12 Kilometers



Recent Timeline
% Live Cover
40
37
34
31
28
25
% Live Cover
Precipitation [cm]
35
25
15
5
Precipitation
Water Volume [ac-ft/yr]
650
550
450
350
250
150
Total Water Export
Water Volume [ac-ft/yr]
175
125
75
Groundwater Extraction
1984
1986
1988
1990
1992
1994
1996
1998
2000

Fig 2

Community-Groundwater Relationships

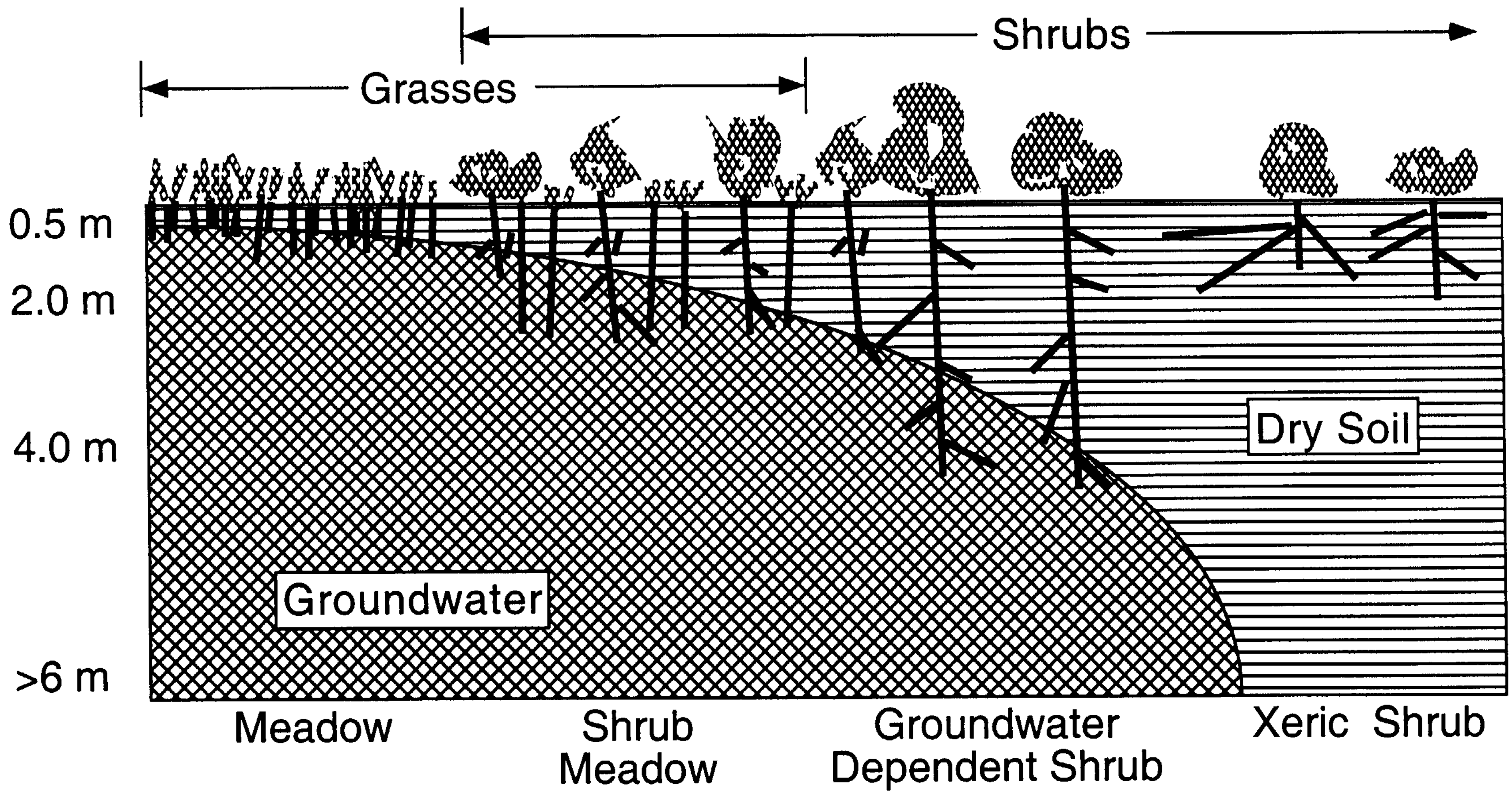


Fig 3

Fig 3

Depth to Water from a Selection of Wells in Owens Valley, California

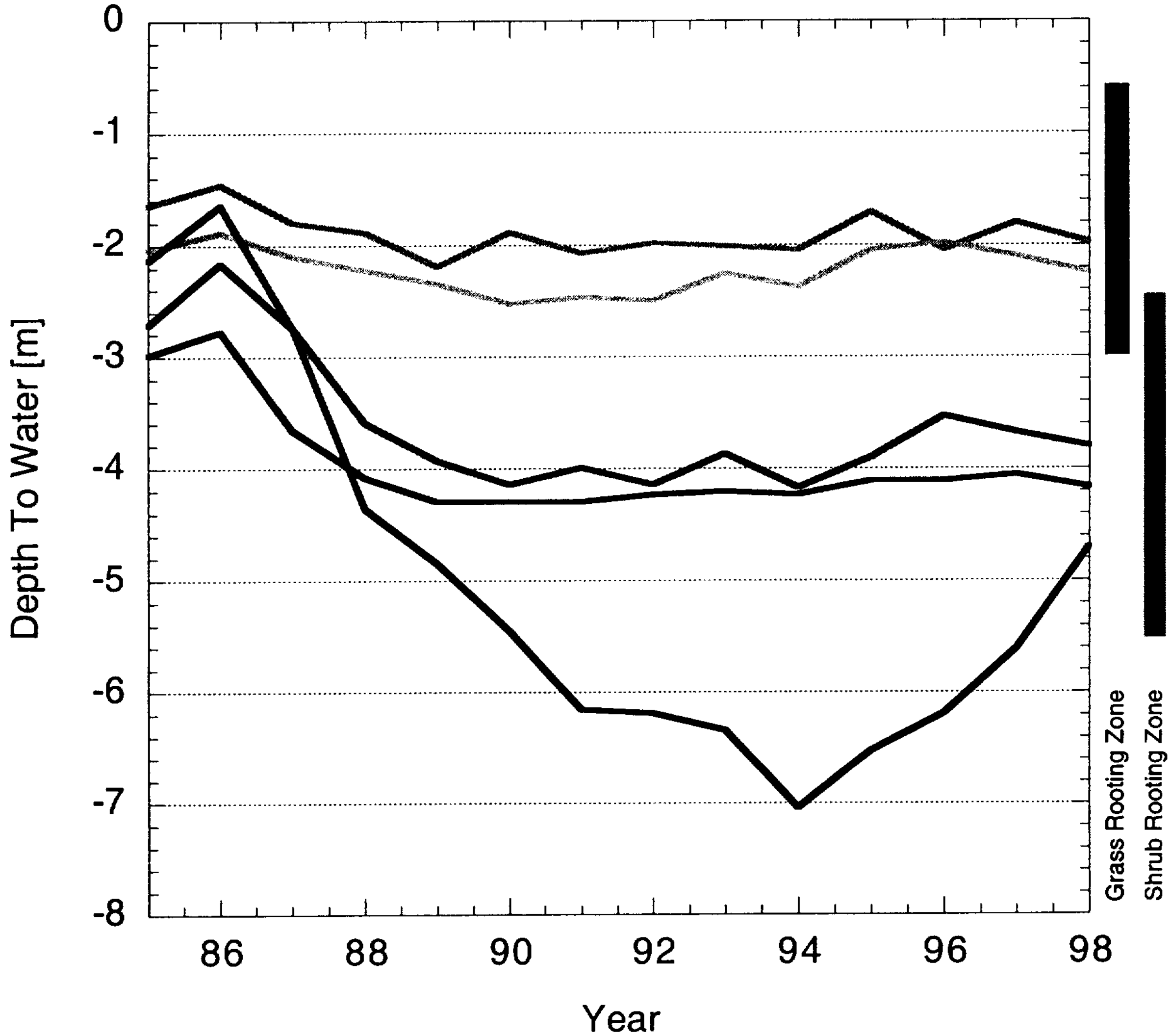
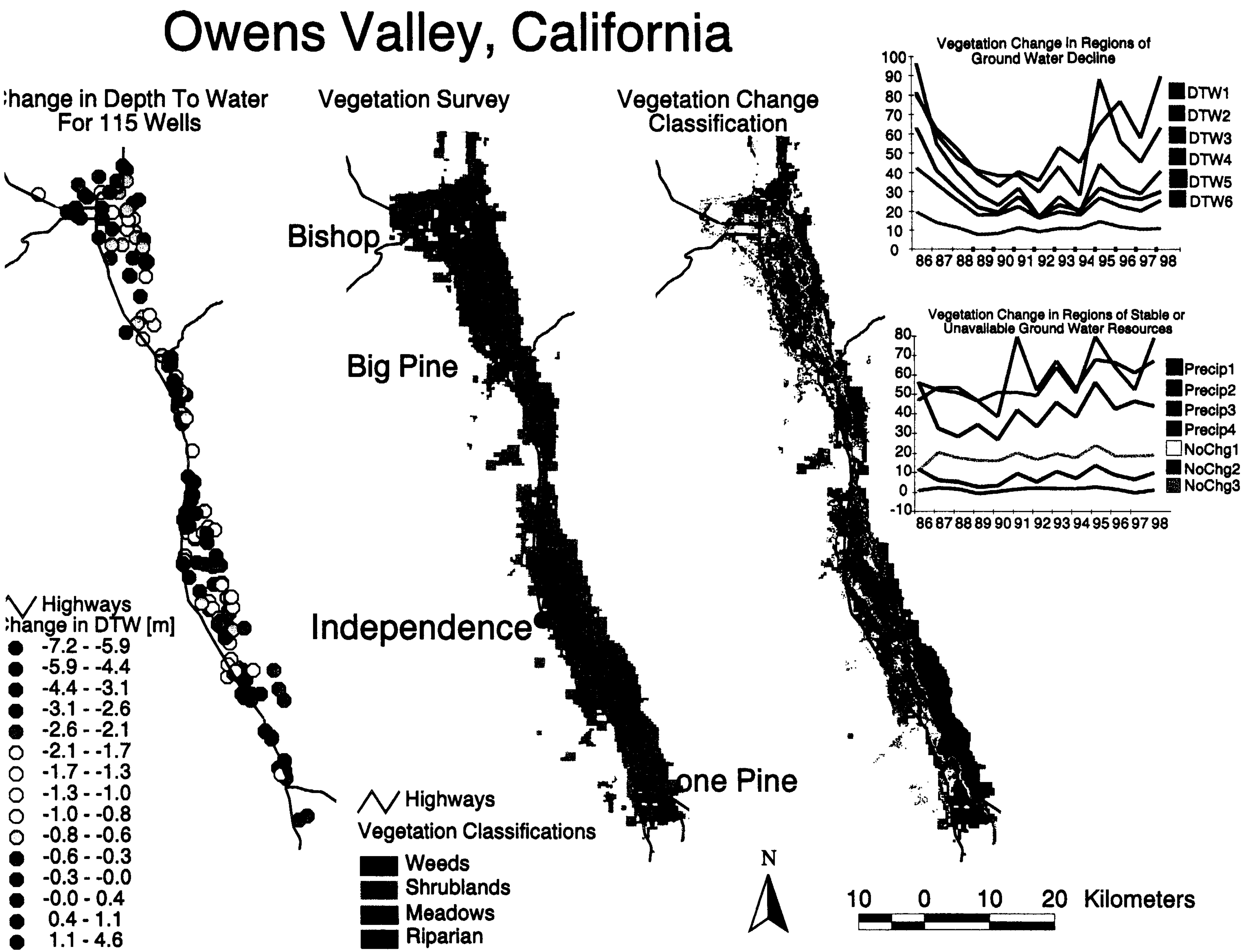


Fig 4



Owens Valley, California
:hange in Depth To Water For 115 Wells
Vegetation Survey
Vegetation Change Classification
Vegetation Change in Regions of Ground Water Decline
100
90
80
70
60
50
40
30
20
10
0
86 87 88 89 90 91 92 93 94 95 96 97 98
DTW1
DTW2
DTW3
DTW4
DTW5
DTW6
Vegetation Change in Regions of Stable or Unavailable Ground Water Resources
80
70
60
50
40
30
20
10
0
-10
86 87 88 89 90 91 92 93 94 95 96 97 98
Precip1
Precip2
Precip3
Precip4
NoChg1
NoChg2
NoChg3
Bishop
Big Pine
Independence
one Pine
Highways
:hange in DTW [m]
-7.2 - -5.9
-5.9 - -4.4
-4.4 - -3.1
-3.1 - -2.6
-2.6 - -2.1
-2.1 - -1.7
-1.7 - -1.3
-1.3 - -1.0
-1.0 - -0.8
-0.8 - -0.6
-0.6 - -0.3
-0.3 - -0.0
-0.0 - 0.4
0.4 - 1.1
1.1 - 4.6
Highways
Vegetation Classifications
Weeds
Shrublands
Meadows
Riparian
N
10 0 10 20 Kilometers

Fig 5

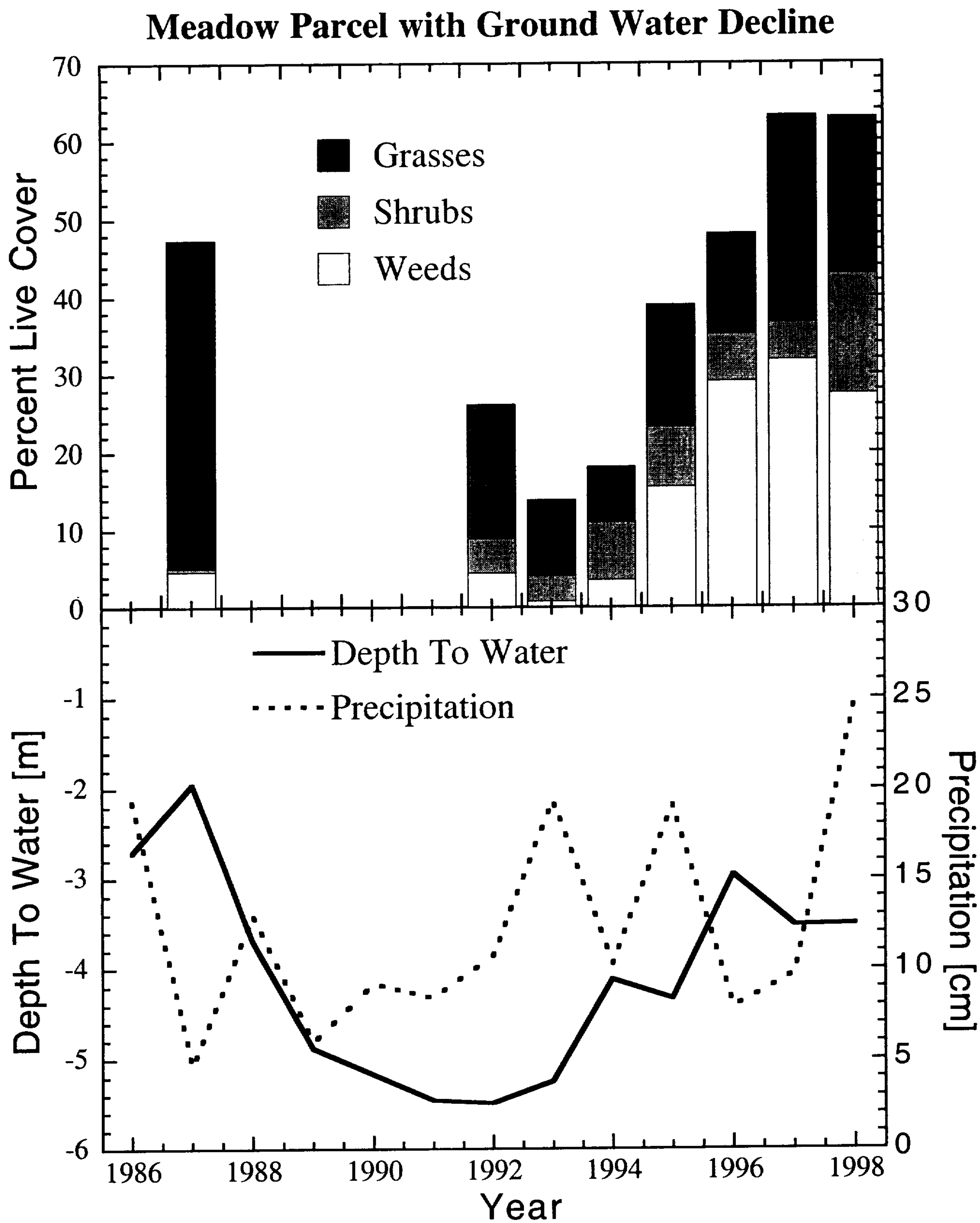

Meadow Parcel with Ground Water Decline
Grasses
Shrubs
Weeds
Percent Live Cover
Depth To Water
Precipitation
Depth To Water [m]
Precipitation [cm]
Year
70
60
50
40
30
20
10
0
-1
-2
-3
-4
-5
-6
30
25
20
15
10
5
0
1986
1988
1990
1992
1994
1996
1998

Fig 6a

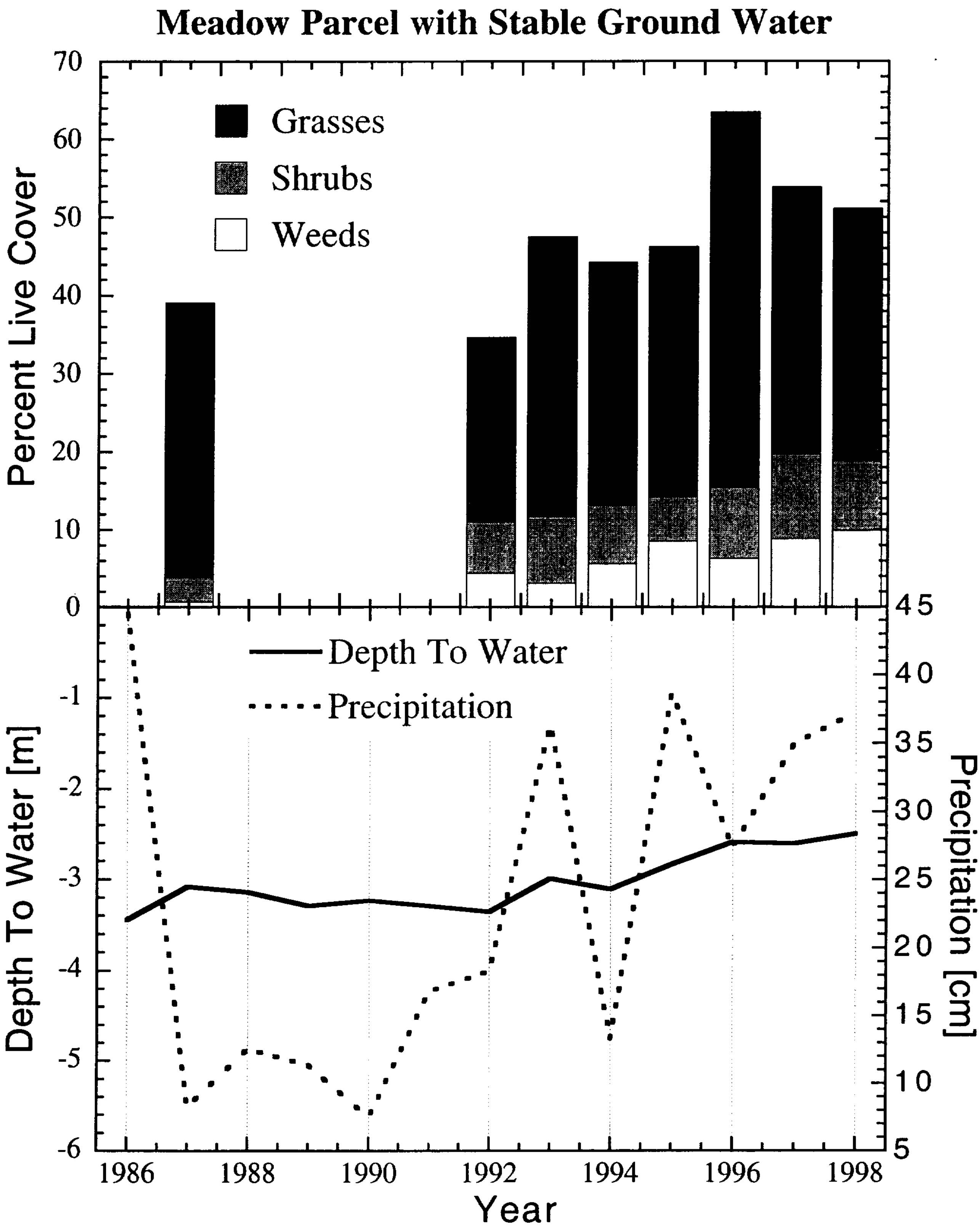

Meadow Parcel with Stable Ground Water
Percent Live Cover
Grasses
Shrubs
Weeds
Depth To Water
Precipitation
Depth To Water [m]
Precipitation [cm]
Year
70
60
50
40
30
20
10
0
-1
-2
-3
-4
-5
-6
45
40
35
30
25
20
15
10
5
1986
1988
1990
1992
1994
1996
1998

Fig 6b

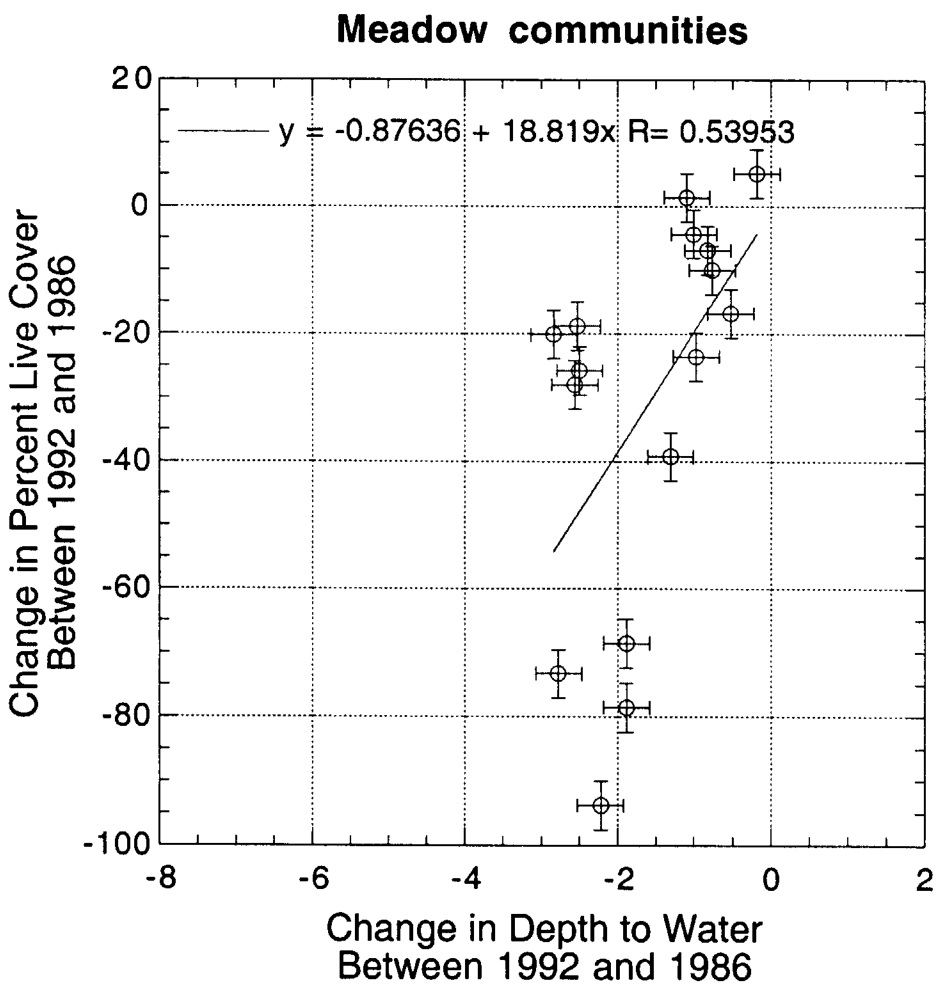

Meadow communities
y = -0.87636 + 18.819x R= 0.53953
20
0
-20
-40
-60
-80
-100
-8
-6
-4
-2
0
2
Change in Percent Live Cover Between 1992 and 1986
Change in Depth to Water Between 1992 and 1986

Fig 7a

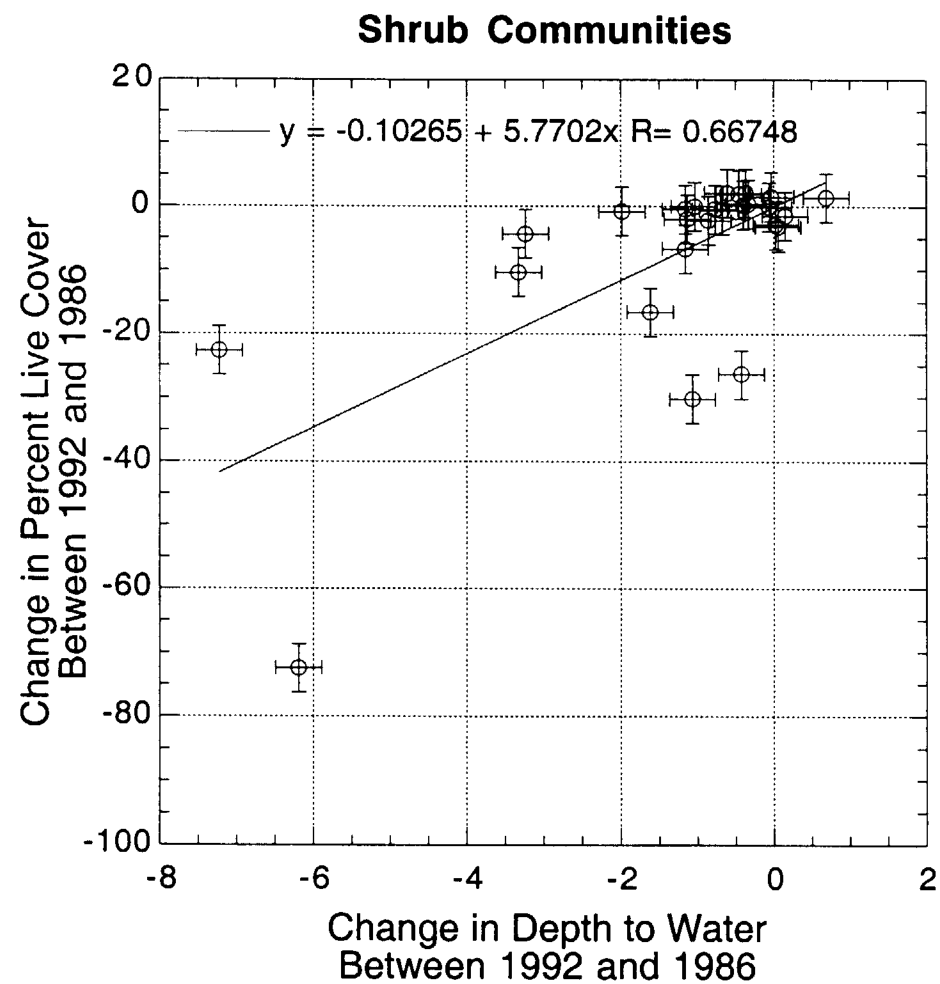

Shrub Communities
y = -0.10265 + 5.7702x R= 0.66748
20
0
-20
-40
-60
-80
-100
-8
-6
-4
-2
0
2
Change in Percent Live Cover Between 1992 and 1986
Change in Depth to Water Between 1992 and 1986

Fig 7b

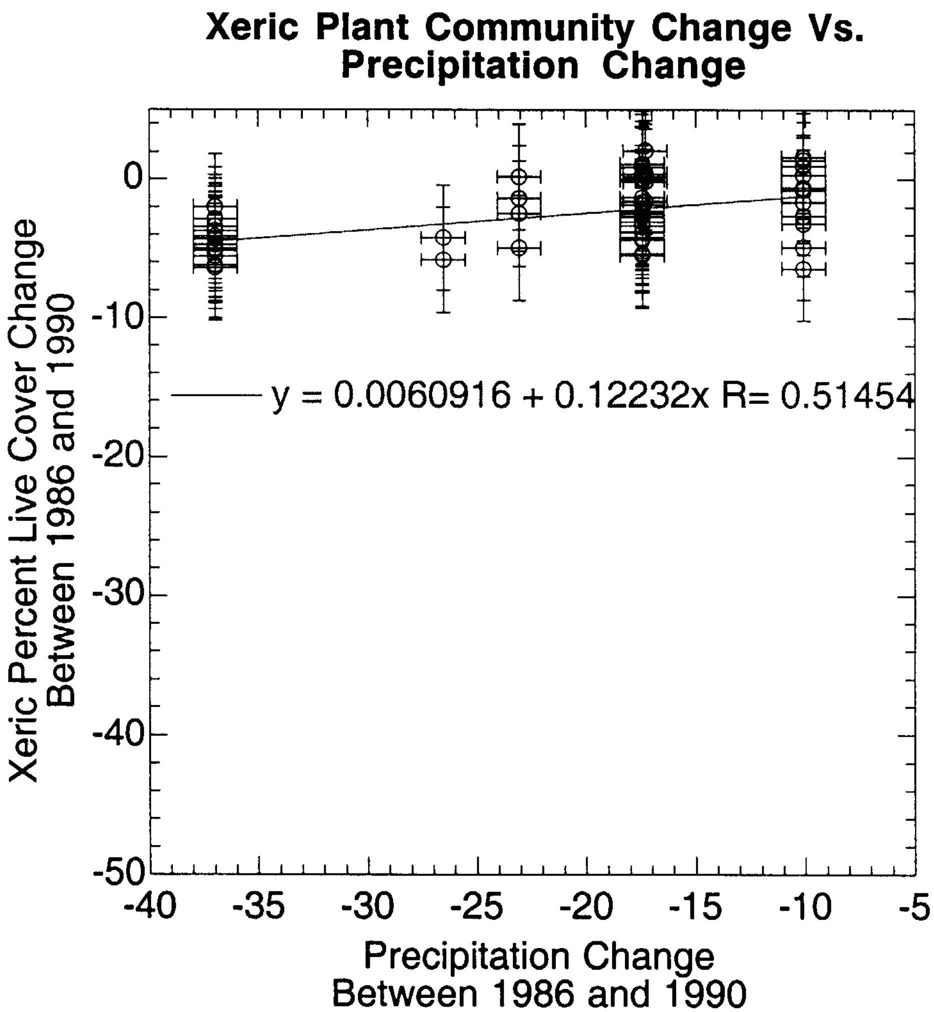

Xeric Plant Community Change Vs.
Precipitation Change
Xeric Percent Live Cover Change
Between 1986 and 1990
0
-10
-20
-30
-40
-50
-40
-35
-30
-25
-20
-15
-10
-5
y = 0.0060916 + 0.12232x R= 0.51454
Precipitation Change
Between 1986 and 1990

Fig 8a

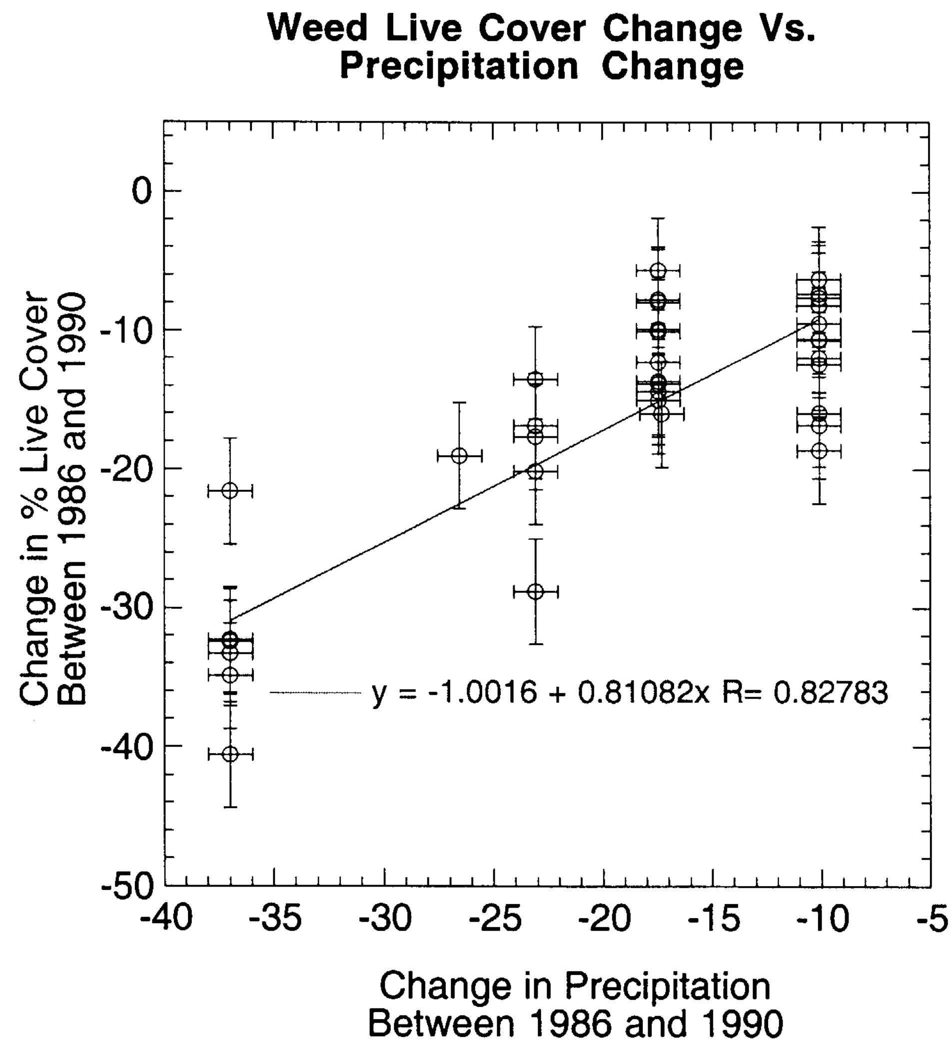
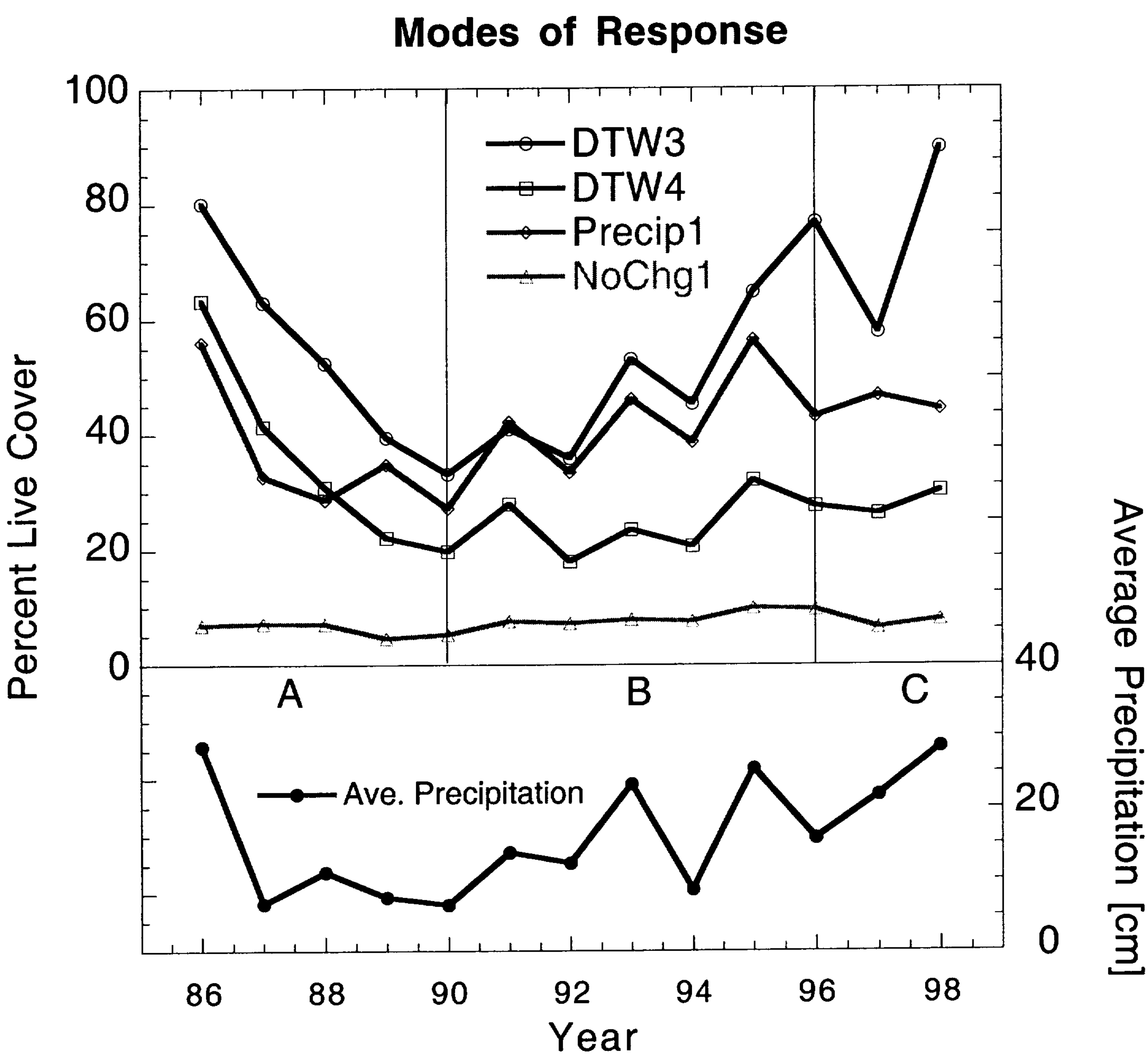

Weed Live Cover Change Vs.
Precipitation Change
Change in % Live Cover
Between 1986 and 1990
0
-10
-20
-30
-40
-50
-40
-35
-30
-25
-20
-15
-10
-5
y = -1.0016 + 0.81082x R= 0.82783
Change in Precipitation
Between 1986 and 1990

Fig 8b



Modes of Response
DTW3
DTW4
Precip1
NoChg1
Ave. Precipitation
A
B
C
Percent Live Cover
Average Precipitation [cm]
Year
100
80
60
40
20
0
40
20
0
86
88
90
92
94
96
98

Fig 9